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PRESENTATION ON FACILITY PROBLEMS IN HIGH-TEMPERATURE STRUCTURES RESEARCH

By Paul E. Purser and Richard R. Heldenfels

Langley Aeronautical Laboratory
Langley Field, Va.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

March 27, 1956

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRESENTATION ON FACILITY PROBLEMS IN HIGH-TEMPERATURE STRUCTURES RESEARCH[1]

By Paul E. Purser and Richard R. Heldenfels

SUMMARY

This presentation is intended to reflect the current general approach of the NACA to the problems of high-temperature structures research facilities. The facilities and problems discussed apply to flight in the Mach number range from 2 to about 20. It is emphasized that this field is one in which the thinking is rapidly changing and the facilities investigations discussed, particularly for the higher temperature range, are in the exploratory stage.

INTRODUCTION

Because of the recent increased emphasis on the long-range ballistic missile and the steadily increasing flight speeds of other missiles and fighter and bomber aircraft, there has been considerable concern expressed in many quarters about the possibility of coping with the high-temperature structural problems that accompany these high speeds. In particular, there has been some concern about the NACA plans for research and research equipment in the high-temperature field. This concern is understandable for several reasons:

> It is apparent to many people that the high-temperature structures problem involves many formerly separate fields of research such as structures, aerodynamics, metallurgy, and physical chemistry so that the work that needs to be done requires cutting across previous organizational lines in both industry and research. This new (or merged) field is growing so rapidly and is so fast-moving that there has not been time to report on some of the things people are doing or planning.

[1]Originally prepared for presentation to a special panel of NACA Subcommittee on Aircraft Structures - Sept. 11, 1955.

Consequently, the NACA staff has assembled a story of current thinking, plans, and status in this area for presentation first to a special panel of the Subcommittee on Aircraft Structures and later to other interested NACA Subcommittees and Committees.

The presentation is intended to give a brief review of the problem areas in the field of high-temperature structural research and of the NACA plans for and status of equipment in this field. First, the whole picture as presently known is presented briefly in order, as the discussion continues, to provide an understanding of how the NACA plans fit into the nation's needs.

GENERAL ENVIRONMENT

Figure 1 shows the temperature ranges of concern to "high-temperature" structures. The figure is a plot of temperature in degrees Fahrenheit on a log scale against Mach number. The curves show stagnation temperature at 50,000 feet (which a body nose or wing leading edge might have to withstand) and the equilibrium or wall temperatures (which would act farther back on the structure). The wall temperatures are shown with no radiation and with ideal black-body radiation at 50,000 feet and with black-body radiation at 200,000 feet. The temperatures are all calculated for air as an ideal gas with constant specific heat, no dissociation, etc. There will be more discussion of this point later. At present it is sufficient to note that the temperatures increase with Mach number in a rather orderly fashion and the values cover the range from what known materials can withstand up to the temperature of the sun's surface and on up into the region of the interior temperatures of some of the cooler stars.

In addition to the temperatures, the heat flux or the rate at which the heat energy goes into the structure is of concern. Figure 2 shows some typical maximum heating rates as a function of Mach number and boundary-layer condition. The heating rate in $Btu/ft^2/sec$ is plotted on a log scale against Mach number for a point 1 foot back on a flat plate considering instantaneous exposure at sea level. These conditions may seem somewhat unrealistic but the values shown are approximately correct for body noses and wing leading edges, and for wing undersurfaces during maneuvers at altitude. As indicated by the approximate equation on the figure, the heating rate is dependent on a number of variables. There is a heat-transfer coefficient K which varies somewhat with temperature and with body shape and Mach number; an almost direct dependence on density and velocity and on the temperature difference between the skin and boundary-layer recovery temperature (which increases with Mach number).

The $\sqrt[5]{l}$ factor indicates a strong dependence on distance from the leading edge for the first few inches and less dependence for stations 1 foot or more back. A similar approximate relation can be written for the laminar case in which K will be smaller by approximately one order of magnitude, and ρ, V, and l will all appear to the 1/2 power. The equation, incidentally, is written for local conditions of Mach number, density, and velocity. This leads to a transient heating condition when aircraft are maneuvering, even though equilibrium conditions may have been reached before the maneuver is started. For instance, when the wing angle of attack is increased the density on the lower surface increases, the velocity decreases but the Mach number also decreases and K increases, with a net result that the heat flux increases. The opposite effects occur on the upper surface and this, then, increases the temperature and heating gradients through the structure.

Figures 1 and 2 have shown that both temperature and heat flux increase in a more or less orderly fashion with Mach number; thus, the heating conditions of concern are set by the Mach number requirements.

Figure 3 shows the speed or Mach number requirements as plots of maximum Mach number against calendar years. The solid line represents the maximum speeds reached by NACA research vehicles and, except for the earlier years where there were some V-2 firings, Bumpers, etc., it represents the maximum speeds reached anywhere with articles big enough to carry research instruments. The dashed line and aircraft designations show the speeds for which articles were being designed (and thus for which data were needed) at any particular time. The two lines are roughly parallel and both show an extremely rapid rise in the last few years. The plateau on the solid line is a temporary limit imposed by rocket motors and instrumentation, and work is under way to overcome it. However, one can conclude from this figure that Mach number requirements are <u>not</u> showing an orderly increase with time. In fact, it appears that any timetable as to when facilities are needed for any particular range condenses to "now."

REGIONS OF INTEREST

Since data are needed for the complete Mach number and temperature range, a look at the type of aircraft for which these data are needed is pertinent. Figure 4 shows three general regions of interest along with types of aircraft pertinent to each region.

In the first region, extending up to Mach numbers of 3 or $3\frac{1}{2}$ and stagnation temperatures of 1,000° F, there are present-day missiles, the next generation of fighters, and possibly the second generation of bombers. The fighters will be exposed to transient heating in acceleration and climb, to high relatively steady temperatures for an hour or so, and will undergo fairly large transients in maneuvers. For the bombers the transients from acceleration, climb, and maneuvers will be less (although the maneuver transients after bomb release may be appreciable) but the duration of steady high temperatures may be several hours. Missiles do not have the long-duration steady-temperature problem but their acceleration and maneuver transients are likely to be quite high. Typical values of expected heating rates in this region range from 1 Btu/ft^2/sec for the X-1B which was not designed as a "high-temperature" airplane, up to 3 for the X-2, 10 for some missiles, and on up into the range between 50 and 100 for possible antiaircraft missiles.

In the second region, which extends up to $M \approx 10$ and possibly on up to 12 or 13, with stagnation temperatures up to near 10,000° F, there are glide rockets, (possibly both manned and unmanned), and the next generation or two of missiles. The proposed hypersonic research airplane which is essentially a low-speed glide rocket will probe into the range up to $M \approx 7$ and is expected to have to withstand heating rates of from 5 to 30 Btu/ft^2/sec depending on the flight plan. Higher speed glide rockets and missiles are likely to undergo heating rates in the range between 100 and 1,000 Btu/ft^2/sec.

In the third region, which extends up to Mach numbers of 20 and above, there are the re-entry bodies of long-range ballistic missiles. These bodies will encounter stagnation temperatures in the 30,000° F to 40,000° F range and heating rates, depending on the flight plan, boundary-layer condition, etc., that may range from less than 1,000 to above 10,000 Btu/ft^2/sec.

FACILITIES FOR LOWER MACH NUMBER REGION

The speed range of immediate interest, and also the one in which NACA has done most research on the structural problems of high-speed aircraft and missiles, covers Mach numbers up to about 4. The next part of the discussion then will cover the facilities used for this research and indicate the type of results obtained for this speed range. Occasionally, however, some of the work described will be applicable to the higher speed ranges.

Any discussion of the structural problems of high-speed aircraft must start with consideration of the nature of the environment to which the structure is exposed. This discussion will begin with a consideration of NACA research concerned with the environment and then proceed to a discussion of research on structures.

Environment Research

Figure 5 classifies the environment research as to types and facilities. First, there are the characteristics of the aerodynamic loads. This is the old problem that has always been with us and which is not drastically changed by increase in speeds. Details of the load distribution and other characteristics of the loading are affected by Mach number, but no new concepts are involved. Consequently, little consideration need be devoted to this problem. New concepts are primarily concerned with aerodynamic heating, i.e., the magnitude of the temperatures that are encountered by high-speed aircraft and rate at which heat is transferred to the structure. These two items are investigated by studies of equilibrium temperatures and heat-transfer coefficients. In addition to determining the characteristics of the heating, means for alleviating the adverse effects of aerodynamic heating is also a topic for research. Such things as aerodynamic configurations that experience the least aerodynamic heating for a given flight trajectory, methods for cooling a structure, or techniques for insulating a structure are subjects that must be investigated.

The facilities in which this environment research is conducted are wind tunnels and jets, rocket models, and research airplanes. Wind tunnels and jets provide ground facilities in which detailed studies of equilibrium temperatures and heat-transfer coefficients can be made. However, the scope of this research is often limited by the characteristics of the available tunnels and jets. NACA research on aerodynamic heating began about 10 years ago utilizing existing wind tunnels which were not particularly well suited for aerodynamic heating research. Since that time a number of facilities, designed specifically for heating research, have become operational and are in use at all NACA laboratories.

Rocket models are well adapted to aerodynamic heating research because they experience actual flight conditions. They have been used extensively for fundamental heat-transfer investigations and to check wind-tunnel results on various types of configurations. This type of research is limited by complexity of the models and the limited amount of data that can be telemetered back to the ground.

Research airplanes have been used relatively little in the past to collect information on aerodynamic heating, although they have provided a large amount of environmental research on aerodynamic loads. There is, however, a project underway for a heating investigation on an existing research airplane, the X-1B, and the advanced research airplane to be discussed later has as one of its purposes aerodynamic heating research.

Figure 6 shows some of the configurations that have been investigated for their aerodynamic heating characteristics, i.e., distribution of equilibrium temperatures and heat-transfer coefficients. Of particular interest is the heat transfer to various shapes of bodies and body noses and the heating characteristics of airfoil sections, particularly flaps where the high pressure on the underside greatly increases the heating. Canopies involving transparent materials, wing plan-form effects and the heat transfer to wing leading edges are important. The nose of a body and the leading edge of a wing experience very high heating rates because they are in a stagnation region and configurations that might be used to alleviate this heating are of extreme importance. For example, blunting the leading edge or providing it with sweep have been found to decrease the heat-transfer rate in this region. Flared skirts are useful for stabilizing high-speed bodies or as a means of decelerating re-entry noses at high altitudes. An example of research on other means for alleviating aerodynamic heating are such projects as the one involving transpiration cooling of a cone.

Although the primary object of this part of the discussion is to present problems concerned with speeds up to Mach number 4.0, the aerodynamic heating research discussed extends well beyond this speed range since facilities and projects do not necessarily follow the classification lines given in figure 4. The bulk of the work, however, is concerned with the lower speeds.

Figure 7 is a photograph of a wind-tunnel setup in which aerodynamic heating research is being done. The particular investigation illustrated was concerned with the melting characteristics of various body shapes utilizing models made of low melting-point alloys. A model in the tunnel shows the initial body shape and the model held by the research scientist shows the shape that resulted after substantial melting had occurred. This particular tunnel is a Mach number 7.0 hypersonic wind tunnel and is just one of many wind-tunnel and jet facilities being used for aerodynamic heating research.

Figure 8 shows a transpiration cooling test setup. The cone has a porous skin through which various fluids and gases are transpired to cool the surface. Test results give flow rates required to maintain various surface temperatures and the work to date has used water, helium, and nitrogen as the coolant.

Figure 9 shows a rocket model typical of many used to investigate aerodynamic heating problems. This particular model is a parabolic body of revolution on which heat transfer and skin friction are measured. It is boosted to high speeds by the booster rockets and contains an internal sustainer rocket. Models such as these have been used to investigate aerodynamic heating up to a Mach number of about 4.0.

Rocket models for investigations of higher Mach numbers become considerably more complicated as shown on figure 10. This photograph shows two four-stage rocket models in position prior to launching at the NACA Pilotless Aircraft Research Station at Wallops Island. The research model is the fourth stage which is the small body at the upper end of the assemblage. Models such as these have attained a Mach number of 10 at an altitude of about 100,000 feet.

Figure 11 illustrates the thermocouple installation recently completed in the X-1B airplane. The installation was made for the purpose of measuring skin and structural temperatures in this research airplane. The temperature of various parts of the skin on the nose, canopy, control surfaces, wing, fin and stabilizer junction, and other points on the body will be measured to determine whether the simple theories of heat transfer apply to all locations on a complicated airplane shape. Also, temperatures of the interior structures will be measured to collect data on heat flow through representative types of airplane construction.

The preceding discussion comprises a rather hasty review of NACA research on the environment encountered by high-speed aircraft, particularly in the Mach number range up to 4.0, but has also indicated some work applicable to higher speed ranges of interest for glide rockets and missiles. This research on the environment constitutes a large part of the NACA effort on structural problems of high-speed aircraft.

Structures Research

Turning now to the structures research, figure 12 indicates research types and facilities. The types of structures research indicated here are classified by the type of environment encountered, rather than by the structural action resulting from the environment. As is shown, the structures research is concerned with the effects of four types of environmental conditions. First is the load-carrying ability of the structures. This is essentially the same problem with which structures research has always dealt but which is now complicated by the three other types of environment indicated, i.e., the high temperatures that result from aerodynamic heating, the rapid heating that occurs when flight conditions change, and finally, the problems that might be called aero-thermo-elastic, which are the combined effects of aerodynamic loads, high temperatures, and rapid heating. High temperatures influence the load-carrying ability of a structure primarily through their effects on material properties with the resulting loss of strength and creep of structures at elevated temperatures. Rapid heating is of interest because it induces thermal stresses which may cause a structure to buckle or experience other undesirable deformations. These thermal stresses may also cause significant reductions in the stiffness of a structure even when they are well below the levels required to produce buckling. These stiffness changes are a particularly significant part of the aero-thermo-elastic problems wherein combined actions may lead to wing divergence, aileron reversal, or flutter.

The facilities used to investigate these structural problems are likewise classified on the basis of types of environment they produce. The testing machine, of course, is the old standby for producing various types of loads on structural elements and components. Ovens and furnaces provide an easy means of generating high temperatures, particularly when the temperatures associated with speeds up to Mach number 4.0 are of concern. These ovens and furnaces are commonly combined with testing machines to provide information on the characteristics of materials and structures at elevated temperatures. Rapid heating of structures presents a more complicated problem. The particular type of rapid-heating apparatus used at the NACA is the radiant heater. Again, the radiant heater can be combined with a testing machine to provide combinations of loads and rapid heating. Combinations of radiant heaters or ovens with testing machines provide methods for gross simulation of high temperatures, rapid heating, and various aerodynamic loadings, but they simulate the true aerodynamic environment only in an overall manner, not in detail. Detailed simulation of aerodynamic heating and loading requires aerodynamic facilities such as jets and wind tunnels, rocket models, and research airplanes. None of these facilities have been used extensively in the past for structures research, although wind tunnels and rocket models have been used for a number of investigations of flutter problems. However, increasing use is now being made of these facilities for research on structural problems.

Figure 13 is a photograph of some compression creep apparatus in the Structures Research Laboratory at Langley. This apparatus combines a testing machine with a furnace for the purpose of investigating the strength and creep behavior of structural elements at elevated temperatures. The particular equipment in place in the testing machine is a fixture for conducting tests on plates, but other fixtures can be placed in the machine for investigating material properties or the structural behavior of columns and stiffened panels. The apparatus in the picture consists of a testing machine, specimen fixtures, data recording apparatus, furnace, and furnace control equipment. This particular furnace has a temperature limit of 600°, corresponding to a Mach number of about 3.0, but will be soon rebuilt to extend the temperature limit to 1,200° which corresponds to Mach number of about 4.0. Several other pieces of equipment similar to that shown here are available in the structures laboratory for determining the elevated temperature strength and creep properties of materials at temperatures up to about 1,800°. Metals are unsuitable for structural applications at this temperature which corresponds to a Mach number of about 5.0.

Figure 14 shows a large furnace that was built for the purpose of testing structural components such as box beams. The particular furnace is 3 feet by 3 feet by 8 feet in size and has a temperature limit of about 900°. In the setup illustrated the specimen is carrying a dead weight load and is undergoing a creep test. By substituting hydraulic jacks for the dead weights, static strength tests can be conducted in this furnace.

Equipment of the type illustrated in the previous two figures is used to investigate the strength and creep characteristics of materials and structures at elevated temperatures. One of the primary objects of these investigations has been the correlation of structural behavior with material behavior. This work has been fairly successful and the strength of plates, stiffened panels, and box beams of many materials at room and elevated temperatures has been correlated with the material stress-strain curves obtained under similar exposure to temperature. Similar efforts have been made to correlate the creep behavior of plates with material creep curves and the initial efforts in this regard have also been successful.

Turning now to considerations of rapid-heating equipment, there are many techniques that can be used to rapidly heat structures, but the particular method used in the Structures Research Laboratory of the NACA is the radiant-heating technique. Two types of radiator are in use, the carbon-rod type and the quartz-lamp type.

Figure 15 is a photograph of a carbon-rod heat radiator. This radiator consists of an array of 3/8-inch-diameter carbon rods that are 20 inches long and spaced 1 inch apart to give a total length of 48 inches. These rods are brought to incandescence by passing electrical current through them and the heat radiated is used to rapidly heat a structural specimen. This radiator has heated specimens as rapidly as 100 Btu/ft^2/sec. This heating rate is higher than any rate contemplated for aircraft in the speed range up to Mach number 4.0 and is sufficiently high to handle most of the problems associated with glide rockets in the higher speed range. It is not capable of generating the heat fluxes produced by re-entry of ballistic missiles. It may also be used to simulate the heat radiated by nuclear explosions.

The maximum power output of this 2- by 4-foot array of carbon rods requires 2,000 kw of electrical energy. The power requirements of rapid-heating equipment are thus quite high and special power sources are necessary wherever they are used. Initially only 225 kw were available in Structures Research Laboratory, but this has recently been increased to 2,000 kw and a budget request has been initiated for a capacity of 10,000 kw. This latter power supply will permit the construction and operation of radiant heaters that can heat both sides of structures as large as 6 by 8 feet.

The carbon rods have a high thermal inertia and about 15 seconds is required to bring them to their operating temperatures of 4,600° F. Consequently, the control of the heat output from this type of heater is rather difficult. In most investigations in which these radiators are used, a mechanically operated shield is needed to control the heating of the specimen. This kind of control usually provides only a single-step input and is not very suitable for simulation of aerodynamic heating. A more desirable radiator could be controlled electrically to give a varying heating rate. The quartz-lamp heat radiator is one that fulfills this requirement.

In the initial development of radiant heaters considerable effort was devoted to tungsten filament types such as industrial heat lamps and it was found that the General Electric Company was actively developing a tubular quartz lamp that very nearly fulfilled our requirements. Development work with the General Electric Company resulted in the 10-inch quartz lamp. This lamp consists of a tungsten filament encased in a 3/8-inch quartz tube filled with an inert gas. This particular lamp is rated at 1 kw and 220 v, but is frequently used for high intensity heating at 460 v and 3 kw. Recently, lamps have become available in the 25-inch length which operates on 460 v for continuous use or which can be operated at twice this voltage for short high intensity heating tests. A 50-inch lamp is also under development and should be available soon. The tungsten filament in these lamps has low thermal inertia and consequently when combined with proper control equipment can give varying heat intensities.

Figure 16 is a photograph of a quartz-lamp radiator. This particular setup shows two 10- by 24-inch radiators heating each side of a structural specimen. Each radiator consists of a double-deck array of quartz lamps that are spaced at 1/2-inch intervals. There are 97 lamps in the 24-inch radiator, and at maximum intensity they require approximately 300 kw of power. In an array such as this the quartz-lamp radiator can provide maximum heating rates approaching the 100 $Btu/ft^2/sec$ obtainable with the carbon-rod radiators. This appears to be about the practical upper limit for these particular quartz lamps, but further development can lead to higher power densities; for example, a 25-inch lamp rated at 5 kw at 600 volts has been produced. Further development can also increase the maximum intensity of carbon-rod radiators.

Figure 17 shows some of the types of tests made with the rapid-heating equipment. The structural specimen is heated by radiant heaters and may be simultaneously loaded by some type of testing machine or loading apparatus as indicated in the sketch, the purpose of these tests then being to investigate the effects of rapid heating alone, or the combined effects of rapid heating with static or dynamic loads, on structural behavior. For example, items that are being investigated include the thermal buckling and maximum strength of structures for various combinations of loads and rapid heating and the effect of rapid heating on the natural frequencies of vibration of a structure to determine how rapid heating influences the effective stiffness of a structure. Also, of interest are thermal deformations of the structure which may occur either with or without applied loads. These deformations may also be interpreted in terms of reduced stiffness of a structure.

Figure 18 illustrates some of the types of construction that have been included in such test programs. The purpose of these investigations is to determine the characteristics of existing types of construction under rapid-heating conditions as well as to develop new types of construction that are less susceptible to the detrimental effects of rapid heating. Thus the test program has included both the mulitweb structure with formed channel webs and the skin stringer type of construction which are representative of current practice. Also investigated have been the corrugated web and a truss-type web which have low extensional stiffness and consequently induce negligible thermal stresses in a rapidly heated structure. These types of construction have been investigated, both for their thermal stress properties and for their load-carrying capabilities. Other types of structures investigated include integrally stiffened construction and the honeycomb core which are promising means of stabilizing the skin of high-speed vehicles. Both of these constructions have been investigated on some wing models tested in a supersonic jet and both constructions were superior to more conventional designs that had difficulty surviving the test conditions.

Figure 19 is an illustration of one setup in which the effects of rapid heating on the characteristics of some box beams were investigated. The box beams included the formed channel, corrugated, and truss-type webs. Each cover of the box beams was heated by the carbon-rod radiators shown above and below the specimen and a pure bending moment was applied through the loading fixture at the end. This is a relatively simple type of combined heating and loading setup in which the heating and loading are gross simulations of the heat and loads expected in flight.

Figure 20 shows a more complicated arrangement for heating and loading a missile wing. This setup uses quartz lamps and numerous load points in an effort to simulate more accurately the distribution of heat and load. Although the photograph does not show the auxiliary control equipment it is evident that detailed simulation requires very complex arrangements of test apparatus. It is thus desirable to have some type of facility in which proper simulation can be obtained without the complexity exhibited here. One such facility is a heated wind tunnel in which the structure can be both heated and loaded aerodynamically.

Figure 21 shows a wing model setup in the preflight jet at Wallops Island, Va., for the purpose of conducting an aerodynamic heating test. The NACA has previously reported much of the work that has been done in this facility in which small wing models have been subjected to aerodynamic heating and loads with the results that several models have experienced dynamic failures as a result of the rapid-heating combined with aerodynamic loads.

High-Temperature Structural Research Laboratory

In 1951 it appeared that the requirements for high-temperature structural research were increasing substantially and that the NACA would need a large facility in which such problems could be investigated. The problem of conducting such research was studied during the following year and the requirements indicated on figure 22 were established for this facility. In general, it was required that the facility be able to simulate the heating and loading encountered by high-speed aircraft and that realistic structural models be accommodated. With regard to the heating, it was necessary that the facility simulate both the magnitude and distribution of the heating. This means that it must either heat the model aerodynamically as in flight or provide some very elaborate control equipment for duplicating the temperatures and heating rates experienced in flight. With regard to the loading, again it was desirable that the facility simulate both the magnitude and distribution of the expected loads and that the loads could be applied in the manner expected in flight, i.e., the structure would be subjected to rapid applications of load at various times during the heating cycle. Since the exact nature of the environment on the structure was not known at that time and is at best only generally understood at present, the conclusion was reached that the only good solution to this facility problem was a very special type of wind tunnel in which the heating and loading would be produced aerodynamically as in flight. It must be a special type of wind tunnel to provide true stagnation temperatures and heat-transfer rates. The design conditions selected covered Mach numbers up to and including 3.0, which was believed to be the probable speed range of man-carrying aircraft during the time this facility would be of most use.

The size of the facility was determined by the structural models it was desired to test. The model criteria were that the facility should accommodate structural components such as wings, bodies, or control surfaces likely to be used on high-speed aircraft and that these models would be of the same type of contruction as the full-size article. The ability to construct built-up structural models fixes a minimum size for the models and consequently determines the size of the test section. Also, the conditions produced in the tunnel must take proper cognizance of the scaling laws associated with aerodynamic heating and loading of structural models and the strain distributions that result. Since the various phenomena under investigation scale in different ways it was concluded that the facility should be as large as possible in order that the models be near full scale. Large supersonic wind tunnels, however, are very expensive so the final compromise was a test section measuring 6 feet in height by $8\frac{3}{4}$ feet in width. This size can accommodate half-scale models of many structural components of future aircraft or complete missiles.

Figure 23 shows the operating range of this facility. Static pressure in the test section is plotted as a function of Mach number and the shaded area indicates the combinations of pressure and Mach number available. For reasons to be discussed shortly, this facility will be a blowdown-type tunnel, thus the approximate running times in seconds are indicated for various conditions. The Mach number range extends from 1.5 to 3.0, although virtually all testing will be in the Mach number 2.0 to 3.0 range. The stagnation temperature is fixed at 660° F, the actual value experienced in the stratosphere at Mach number 3.0. Stagnation temperature cannot be varied during a run, but can be preset at any desired value between about 100° F and 660° F. On the right of the chart the pressure has been interpreted in terms of altitude for a half-scale model. To get the correct temperature distribution in a scale model of a structure, the scale model must be heated faster than the full-scale article. Consequently, in the wind tunnel the half-scale model must be run at higher densities than a full-scale article to obtain the correct Reynolds number and thus correct heat-transfer coefficient. The altitude scale indicates the full-scale altitude for a half-scale model and shows that at Mach number 3.0 the running conditions simulate the heating encountered in the altitude range between 40,000 to 50,000 feet, whereas at Mach number 2.0 the altitudes simulated are from 10,000 to 35,000 feet. In the test of a half-scale model that is heated faster to provide the proper temperature distribution, significant events occur faster (by the square of scale factor) so that the running time in the tunnel corresponds to 4 times the time during full-scale flight, thus a 30-second test of a half-scale model will produce the temperatures encountered by the full-scale article in a 2-minute flight. As previously indicated, this facility is a blowdown-type tunnel. It will be a blowdown wind tunnel primarily because of the tremendous amount of power required for the continuous operation of such a facility. For example, the maximum power required is at Mach number 2.5 on the upper curve. At this condition the tunnel would require $3\frac{1}{2}$ million horsepower for continuous operation. However, by using a blowdown tunnel a 20,000-horsepower compressor running for less than 2 hours will store sufficient air to give the running times shown on the figure. It may be of interest to note that the test conditions indicated can be obtained without a subsonic diffuser. The supersonic discharge is thus a gigantic jet engine that has a maximum thrust of about 750,000 pounds.

Figure 24 shows an architect's sketch of the facility which gives an indication of the size and arrangement. The air is stored in the bottles to the left which are approximately 70 feet high. The test section is housed in the tallest section and the tunnel discharges through the opening indicated at the right. The tunnel controls and data recording equipment are housed in the concrete building in front of the test chamber and the other small building houses equipment for stagnation temperature control.

Figure 25 illustrates the general arrangement of the facility. The air storage field, pressure control valves, heat accumulator, supersonic nozzle, and test section are indicated in black, the stagnation temperature controls in gray, and auxiliary equipment in dark gray. The heat accumulator which fixes the stagnation temperature of the air before it is expanded through the nozzle is a regenerative-type heater that stores heat in thin stainless steel sheets between runs and then transfers this heat to the airstream during the test. There are approximately 600,000 pounds of 0.025-inch-thick stainless steel sheet in this accumulator.

Figure 26 shows a cross-sectional view of the nozzle and test section of this facility. This particular nozzle shown is one that produces a Mach number 3.0 air flow and a schematic model is shown in the test section. The nozzle walls are flexible plates pulled down against templates. By changing templates the Mach number can be changed. Three sets of templates are being made to give Mach numbers of 2.0, 2.5, and 3.0. As illustrated here, models may be mounted in the floor of the test section on a turntable which controls the angle of attack and thus the aerodynamic loads on the model. This turntable is actuated by a hydraulic system controlled by a servo. The angle of attack can be programmed during a test so that the model experiences pull-ups or similar load applications. Other arrangements of models include bodies or complete missiles sting-mounted in the center of the tunnel.

Since this tunnel duplicates the aerodynamic heating experienced by aircraft structures, the tunnel itself experiences the same heating in the test section, but in the nozzle throat where the flow is very dense the tunnel experiences more severe heating than any model expected to be put in it. Consequently, one of the problems to be investigated in the facility is also involved in its design. At the throat, the flexible plates which are $1\frac{1}{16}$ inches thick steel could experience very rapid heating and consequently high thermal stresses. These stresses could be high enough to permanently deform the plate; thus it was necessary to devise some means of protecting the nozzle walls from the severe heating. Since the maximum temperatures expected in this tunnel are moderate, a practical approach was to insulate the tunnel walls in the area between the entrance cone and the test section. Numerous means of insulating the walls were investigated and the final solution was to use a phenolic fiberglas laminate 0.050 inch thick. This laminate is a sufficiently poor conductor of heat to keep the steel plate below 200° F in any contemplated run.

The type of test program planned for this facility will include rapid aerodynamic heating of various types of structures such as wings and fuselages that incorporate both conventional structures and structures specifically designed to alleviate thermal stress. In addition to the heating, the structure will be subjected to aerodynamic loading during the heating cycle to determine combined effects of heating and loading and to investigate any aero-elastic or flutter problems that may be encountered.

This facility is now under construction with all major components under contract. The foundations are nearing completion and the erection of buildings and equipment will begin soon. The tunnel should begin operating in late 1956.

Concluding Remarks for Lower Mach Number Region

This concludes the discussion of our accomplishments in the fields of aerodynamic heating and structural design in the speed range up to Mach number 4.0. In addition, some plans for future research have been indicated. Although much has been accomplished already, the existing problems are so numerous that a much greater effort is needed to establish the characteristics of the environment, find means to alleviate the severity of aerodynamic heating, establish the range of usefulness of present methods of structural design, and to devise new types of construction that are not susceptible to the detrimental effect of aerodynamic heating.

The remainder of the discussion will be devoted to facilities for research in the higher speed ranges.

FACILITIES FOR HYPERSONIC REGION

Environment

The discussion for lower Mach number began with a discussion of environment, figure 27 extends that discussion to higher speeds. The temperatures, pressures, and velocities are the same as those previously discussed except that the values are higher for the hypersonic speeds. The temperatures at these speeds, referring back to figure 1, went up to that of the sun's surface and more. Now, granted that these extreme temperatures may not exist as one normally thinks of temperature, but when the air is compressed on a body moving through it, the energy is certainly there. It may appear as dissociation, ionization, other molecular degrees of freedom, etc., but the high energy level exists.

At these temperatures (and even at lower values) chemistry enters the picture. One example of this chemical entry is the proposal that re-entry bodies be cooled (or absorb heat) by allowing the outer layer of steel to melt and slough off. This condition has been simulated in low-temperature wind-tunnel tests by making models of Wood's metal and melting them with aerodynamic heating. In an attempt to get more realistic conditions some tests were made with preheated steel rod specimens in the 700° F, M = 2 preflight jet at Wallops Island, Va.

Carbon and chrome-molybdenum steels burned rather than melted when inserted into the jet after being preheated to about 2,400° F; stainless steel and copper did not burn. Under the test conditions the air jet actually tended to cool the specimen and also the Mach number was low enough that the air was not dissociated or ionized. Under more real conditions where the air will be heating the metal rather than cooling it and where the air, through its temperature, dissociation, and ionization, may have considerably increased chemical activity the stainless steel and copper may also burn.

In order to avoid the preheating requirements and to obtain more nearly correct aerodynamic heating, the Ames Laboratory built a hot subsonic jet using acetylene burners to get temperatures of about 2,600° F. Some exploratory tests were made of two steel models in this jet. The models were 3/8 inch in diameter - one was sharp pointed and one had the nose blunted to a 1/16-inch radius. The pointed body came up to temperature very quickly and burned. The greater heat capacity of the blunted nose protected it at these temperatures but from the glow it appeared that it too would burn in a somewhat hotter airstream.

In some other tests a heated strip of titanium alloy burned very nicely in a still nitrogen atmosphere - so oxidation is not the only chemical activity of concern. It appears in general that chemistry is to be a real part of the high-speed structural environment. It is believed that the aerodynamics and materials aspects of the problem are pointing toward a merging of the fields of structures, aerodynamics, metallurgy, and chemistry in high-temperature structural research and design.

Structural Research Equipment

Having considered the environment for the higher Mach number range, consideration may now be given to the equipment that may be needed for research in this range. Figure 28 shows a listing of some of this equipment, and, although at first glance, it appears primarily to be aerodynamic rather than structural, the figure is not mislabeled. The asterisks indicate those items that are actively producing data of interest to this field. The other items represent ideas that are being studied in efforts to learn what can be done to get the required data.

The items are broken down arbitrarily into three groups: Ground, Flight, and Combination. Each item will be discussed briefly but first it is important to re-emphasize that the unstarred items are in the exploratory, planning, or small-scale laboratory study stage.

Supersonic true-temperature tunnels.- By "supersonic true-temperature tunnels" (figure 28) are meant those in which the air is heated (usually by metallic heat exchangers) so that after being expanded through the supersonic nozzle the static temperature is representative of the atmosphere or stratosphere, that is between $\pm 70^{\circ}$ F rather than at -300 or -400° F. Most supersonic tunnels are heated only enough to prevent moisture condensation or air liquefaction in the test section. But a few, like the pre-flight jet at Wallops, the new large structures jet at Langley and some other small jets now being built, are heated sufficiently to provide duplication of true air conditions. Enough is believed to be known at present to allow true-temperature tunnels to be built with stagnation temperatures up to 1,800° to 2,000° F which will cover Mach numbers up to near 5. To go to higher speeds, however, and still get the same quality of duplication of true environment as discussed for the new structures jet at Langley, other equipment will be needed. Some of the other items on figure 28 represent ideas being studied along these lines.

Ceramic heat exchangers.- Another possible means of heating the air is to use ceramics rather than metals in the heat exchangers. Figure 29 shows such a jet schematically and lists the ceramics presently being considered for such use. The stagnation temperature will be limited to somewhat below the melting point of the ceramic - the listed melting points show the range we might be able to cover, 3,400° F to 5,900° F. Other problems, however, must also be considered, such as: Magnesia has a high vapor pressure and is subject to breaking up at high temperatures, and thoria is somewhat radioactive. In general quite a lot is known about ceramics but in particular enough is not believed to be yet known to permit the straightforward design of even a 1-inch-diameter 3,000° F jet. Consequently Langley is now building a small laboratory-scale heat exchanger to establish some design principles and determine just what might be attainable in terms of temperature, Mach number, and test altitude.

Special compressors.- Air can also be heated by rapid compression; thus consideration must be given "special compressors;" these include such equipment as the Ames hypersonic gun tunnel (fig. 30). This equipment consists of a long tube (20-mm inside diameter) containing air, a piston, and a powder charge. The powder is ignited and pushes the piston down the tube compressing the air; the valve is then opened and the air is discharged through the hypersonic nozzle. The air is heated by the compression and also by shock waves (set up by the piston motion) bouncing back and forth in the tube. This equipment has been operated at stagnation temperatures of over 6,000° F, Mach number of approximately 7, test altitude of 100,000 feet, for about 1 second. This sounds very good but the air under these conditions caused very bad erosion of the compression chamber, valve, and nozzle. As a result of this the gun tunnel is now being operated only at temperatures up to 2,000° F until more is learned about how to protect the equipment.

The Langley Laboratory is building a pilot model of an "isentropic" compressor that should be somewhat less subject to erosion but which will also be limited in maximum temperature. In the isentropic compressor the piston is driven by air metered from another source so the piston motion is controlled and will not set up the bouncing shock waves. This equipment will be limited to a maximum temperature of about 3,000° F its initial operation and probably will still have to be in the 2,000° F range until more is learned about handling such hot high-pressure air. When more is learned about this the temperature ranges of both items can be increased by preheating the air in the compression chamber.

Chemical jets.- Another potential source of hot high-energy gas streams for research work is the chemical jet. Figure 31 lists three possibilities, including air. The chemical contents of the jets, it will be noted, are quite different. The air jet should retain its familiar 78-percent nitrogen, 21-percent oxygen, etc. up to at least 5,000° F. The ethylene-air jet has about the right nitrogen content but is deficient in oxygen and also has appreciable carbon and hydrogen compounds. The acid-ammonia rocket jet is deficient in both nitrogen and oxygen except that at high temperatures the water vapor may tend to act very much like free oxygen. At any rate it is apparent from the listed values of presently available maximum temperatures that high temperatures are easier to reach with chemical jets at present and for that reason Langley is building small models of such jets to try to determine how much effect the chemical differences cause and how much use can be made of the chemically incorrect jets.

Shock tubes.- Another item that may be considered a "special compressor" is the shock tube. These are in rather extensive use at various places for the study of gas properties at high temperatures and they may prove quite useful as high-temperature aero-structures research equipment. As shown on figure 32, the shock tube consists of a high-pressure chamber, a diaphragm, a low-pressure chamber, and a weak seal at the end. In operation the high pressure is built up to a desired value, the diaphragm is broken, and the high-pressure gas drives a shock wave down through the low-pressure chamber. This device will then provide stagnation temperatures of 10,000° F or over, Mach numbers up to about 2.5, and test altitudes down to sea level with test durations of 1 to 2 thousandths of a second. By inserting the entrance of a hypersonic nozzle in the low-pressure chamber, the Mach number can be increased to 10 or more at the expense of an increase in test altitude to about 100,000 feet. The extremely short test times available with this type of equipment present tough instrumentation problems but so far it is the only ground item that will produce stagnation temperatures of the order of 10,000° F in a moving air stream. Consequently, NACA is working with pilot models to evaluate the utility of the shock tube and to develop research techniques for its use. Incidentally, the short test time should be helpful from the standpoint of equipment protection requirements.

Furnaces and radiators.- The earlier discussion covered the present status of furnace-and-radiator-type equipment and indicated our fairly extensive use of such items. With presently available equipment, temperatures over 5,000° F or 6,000° F will probably not be possible except with the sun furnace or the high-intensity electric arc.

With a sun furnace, which is essentially a parabolic mirror for collecting the sun's radiation and focusing it at one spot, it appears possible to get temperatures in the range from 6,500° F to 8,000° F and heat fluxes of the order of 2,000 $\text{Btu}/\text{ft}^2/\text{sec}$. Such a device would be extremely useful, particularly for some materials work. Convair is using some small ones and a large one probably should be built; at present, however, the NACA has no such plans.

The high-intensity electric arc offers the possibility of achieving temperatures somewhat higher than the sun furnace and NACA is investigating it to see just what utility it might have.

In general, furnaces and radiators are limited by the lack of airflow. For some uses this can be overcome by using them to heat models mounted in cooler air jets. By this means, it is possible to get an approximately correct temperature distribution but the heating will be incorrect; i.e., the air will be cooling the model rather than heating it and the nose will undergo the greatest cooling rather than the greatest heating. This scheme is useful, however, and is being exploited where applicable.

??.- The last item of purely gound equipment listed in figure 28 is the as yet unknown ideal for which a search is now being made, since none of the items already discussed will allow true duplication of all the conditions in the higher speed range.

Projectiles and combination equipment.- Figure 28 lists three items of flight equipment. In order of speeds attained to date: projectiles are the fastest and airplanes are the slowest; as for size and test duration the order is reversed, airplanes are the largest and have the longest time of flight and projectiles are the smallest and have the shortest flight time.

Projectiles, despite the instrumentation troubles caused by their small size and short flight times, do offer considerable promise as research tools. Although some work has been done with fragments from shaped charges and similar explosives the fastest flights of projectiles of known, predetermined, shape and size have been made with the Ames light-gas gun illustrated on figure 33. This gun consists of a powder chamber, piston, helium compression chamber, seal, model, and evacuated barrel. The powder is ignited, the piston compresses the helium, which in turn shears the seal and drives the model out through the evacuated barrel. A 0.22-caliber pilot model is in use at Ames and has provided projectile speeds of over 15,000 fps. With a larger (20 mm) gun now in the design and construction stage it is believed that speeds approaching 20,000 fps will be obtained. This equipment will then provide stagnation temperatures of over 25,000° F and effective test altitudes ranging from sea level on up since gun launched projectiles can be fired into pressurized ranges with controlled atmospheres.

Lower-speed projectiles fired from powder guns can also provide useful information; some work along this line is being done at both Ames and Langley, but the most highly developed use of such guns has been in the Ames supersonic free-flight tunnel. This tunnel is illustrated in the top of figure 34. Here the model is fired upstream into a long, constant Mach number, test section of a supersonic tunnel. The tunnel air speed and projectile velocity are additive thus giving higher velocities than either device alone could give. In addition the major part of the stagnation temperature comes from the projectile kinetic energy so the tunnel is not required to handle such hot air. This equipment has been used extensively to study the factors affecting boundary layers at high speeds which are important because of the factor of 10 in the difference between laminar and turbulent boundary-layer heating.

On the lower part of figure 34 is illustrated a "re-entry tunnel" that is somewhat kin to the free-flight tunnel. Here the test section is a long supersonic nozzle shaped so that the air density varies along the nozzle in the same exponential fashion that it varies with altitude in free air. Thus a model fired upstream into this nozzle will undergo the same increasing density that a re-entry body undergoes in coming down through the atmosphere. The scaling laws, as far as is now known, are such that the combination of small size, short test time, and density control in the tunnel can be arranged to give good simulation of the real problem. In order to evaluate this scheme Ames is building a small pilot model re-entry tunnel to use with the 0.22-caliber light-gas gun. If present expectations are realized, naturally efforts will be made to design a larger tunnel to use with the larger light-gas gun.

Rocket models.- Now to return to the flight equipment: figure 6 covered the rocket-model program fairly well. Since this is the only way known at present for really getting true duplication at the high speed with instrumented articles, NACA is in the process of extending these tests to higher speeds as rapidly as rocket-motor and instrumentation limits will allow. For an illustration of the range of test conditions that can be covered, some typical rocket model trajectories are shown on figure 35. Here are plots of altitude against range for three types of rocket flight plan. The solid portions of the lines indicate powered flight and the dashed portions show coasting flight. The maximum speed, of course, is at the end of the last solid line. The straight-away trajectory is the simplest and provides the highest speeds in general for a given propulsion system; however, it has the disadvantage of placing the data-gathering portion of the flight at very high altitude which increases the instrumentation problems, also the models go to extreme ranges (500 or 600 nautical miles) which requires a long range sea search or clearance. The Navy, incidentally, has been most cooperative in making these sea searches for us and in moving their training fleet out of the area on firing dates. To avoid or lessen some of these problems, plans at Langley are to use the re-entry type trajectory where the maximum speed is obtained on the way down after the model and part of the booster system have coasted over the peak of the trajectory at lower speeds. As noted on the figure, the Lewis Laboratory is using a similar flight plan with their air-launched models.

Airplanes.- The NACA is planning to extend the X-1 and ~~X-2~~ work mentioned earlier into the hypersonic range with a new research airplane. This airplane is designed to operate at Mach numbers up to near 7 over an altitude range of several hundred thousand feet. An envelope of design flight altitude against Mach number for such an airplane is shown on figure 36. With present knowledge, use of the full altitude potentialities of the aircraft will probably be impossible because of heating during re-entry but such an airplane will allow detailed measurements of the magnitude and distribution of heating rates, temperatures, stresses, deformations, airloads, etc., and most important will provide operating experience in this speed range with the actual full-size aircraft.

Equipment Summary

To summarize briefly, figure 28 is again referred to. In order to provide data in the higher speed range with any of the listed items of equipment, or with whatever new ideas that may arise, a considerable effort will be needed in obtaining operating experience and in developing research techniques and instrumentation.

True-temperature tunnels probably can be made to operate up to the range of 6,000° F or 7,000° F sometime in the future, if the materials problem of containing and directing the required hot high-pressure air can be overcome.

Chemical jets will allow a temperature range of 5,000° F to 6,000° F to be reached sooner and more easily but the effects of gas composition and chemistry on the results obtained need more study and evaluation.

Shock tubes, despite their short test times, will provide temperatures up in the 10,000° F range and should prove quite useful.

Furnaces and radiators offer the possibility of reaching temperatures of from 6,000° F to 8,000° F. The high-intensity arc, which may go higher in temperature, needs more study at present. This general type of equipment should prove quite useful for materials work and either alone or when combined with cooler air jets will be useful for actual structural research.

Rocket models and airplanes are the only presently known items that will provide complete true duplication of the whole environment. Rocket models need more effort on rocket-motor and instrumentation development and for airplanes, naturally, at least gross answers must be obtained to some of the problems before even research airplanes can be designed and built.

Projectiles and the special combination tunnels should prove extremely valuable despite their size limitations.

CONCLUDING REMARKS

In conclusion, the following general observations can be made:

The field of aeronautical research is now a fast-moving one, and data appear to be needed "now" over essentially the complete conceivable Mach number and temperature range.

The fields of structures, aerodynamics, metallurgy, and chemistry appear to be merging rapidly and all are becoming integral parts of the field of high-temperature structures.

Actually none of the ground equipment discussed provides completely adequate duplication or simulation of flight conditions but it is felt that each item can contribute some answers to the whole problem.

With respect to status of research equipment, where the way is known facilities are being provided and where knowledge is limited, work is progressing at laboratory scale to learn what to do. NACA is giving the best possible attention to flight work and, although it is too early to say what ground equipment is needed, the needs are believed to cover the whole temperature range.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 11, 1955.

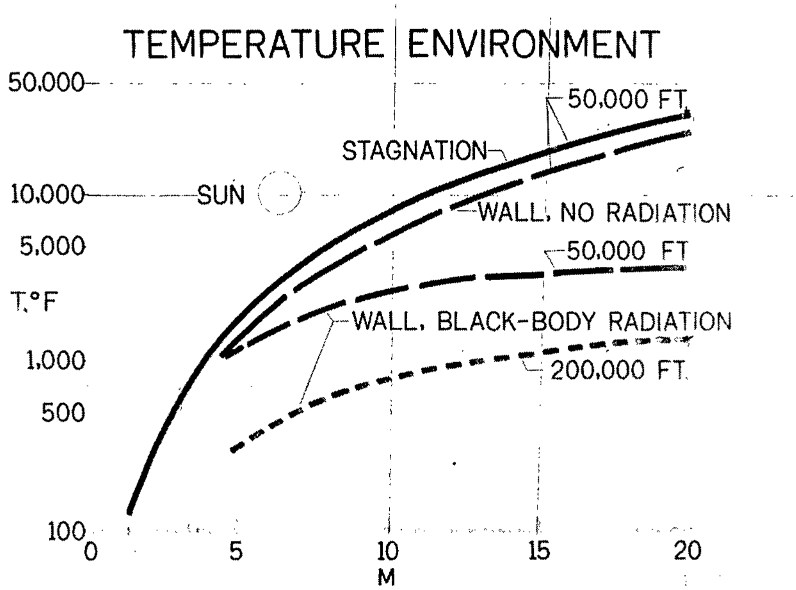


Figure 1. L-254

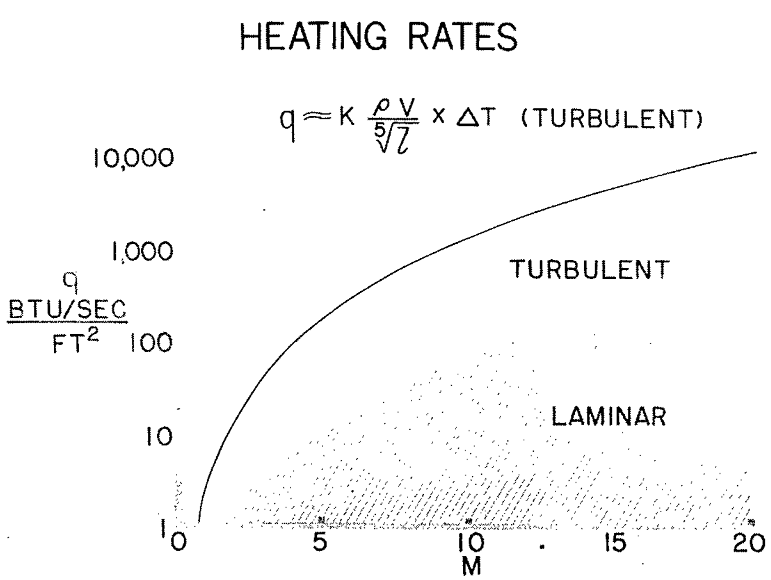


Figure 2. L-253

SPEED REQUIREMENTS

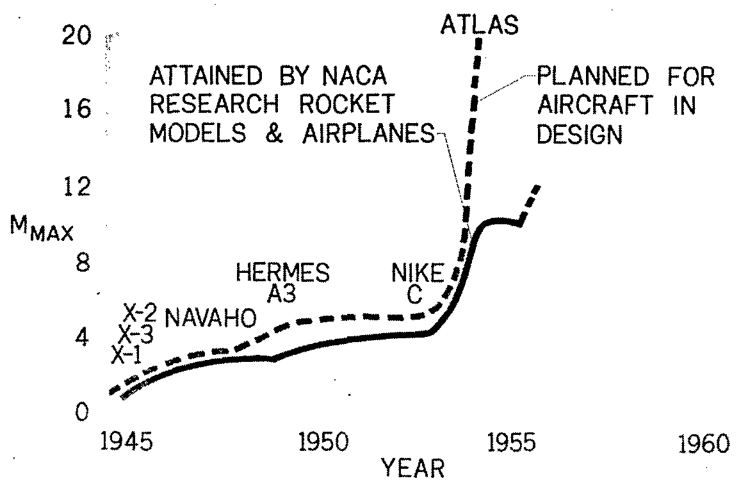


Figure 3. L-255

REGIONS OF INTEREST

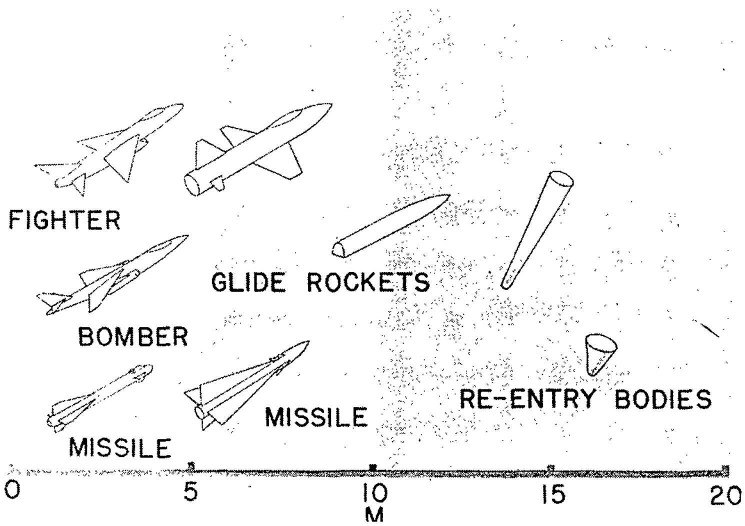


Figure 4. L-256

ENVIRONMENT RESEARCH

TYPES

- AERODYNAMIC LOADS
- AERODYNAMIC HEATING
- HEAT ALLEVIATION

FACILITIES

- WIND TUNNELS AND JETS
- ROCKET MODELS
- RESEARCH AIRPLANES

Figure 5. L-257

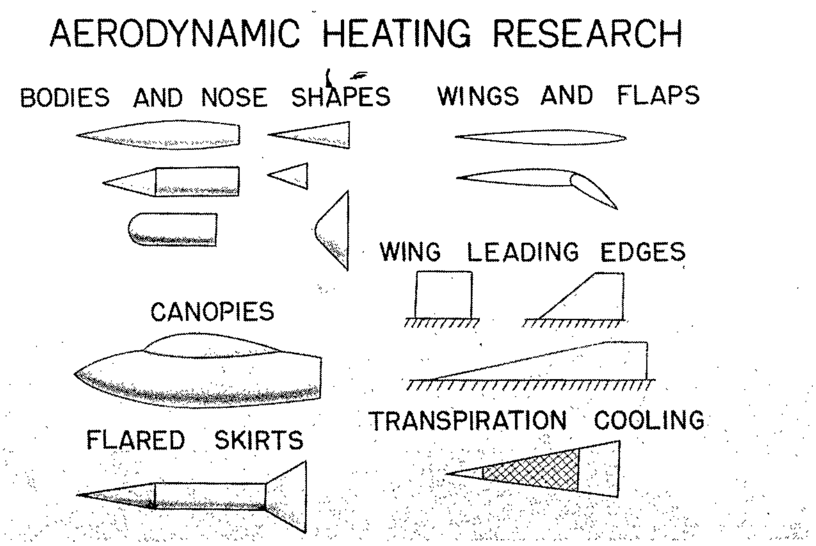


Figure 6. L-258

11-IN. HYPERSONIC WIND TUNNEL

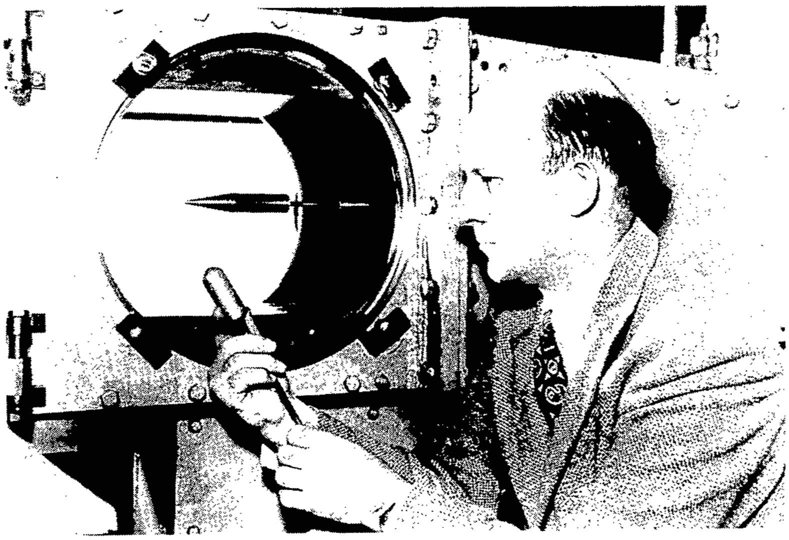


Figure 7. L-259

TRANSPIRATION COOLING TEST

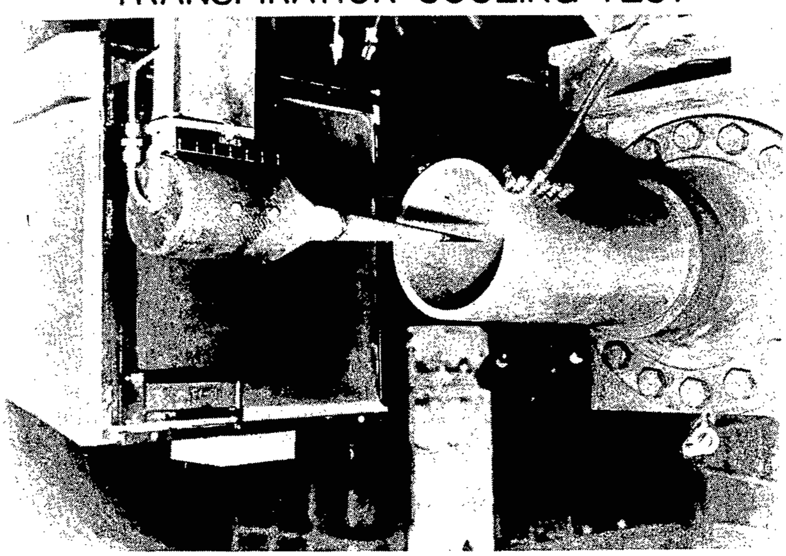


Figure 8. L-260

ROCKET MODEL
AERODYNAMIC HEATING RESEARCH

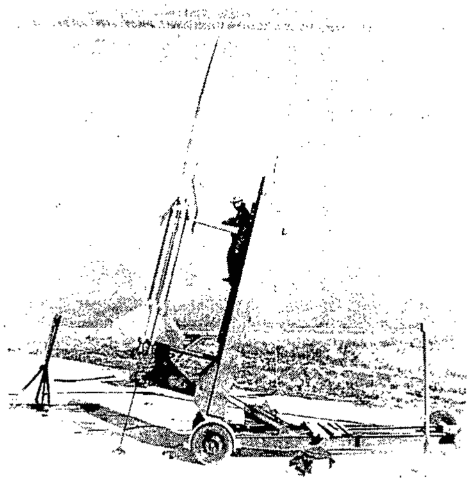


Figure 9. L-261

HYPERSONIC ROCKET MODELS

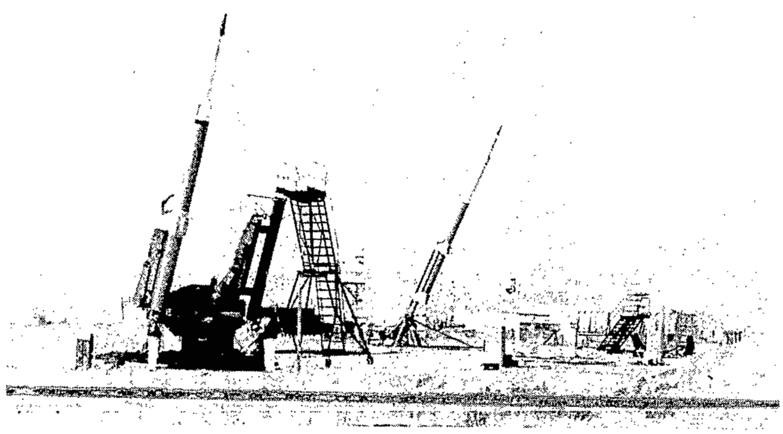


Figure 10. L-262

X-1B THERMOCOUPLE INSTALLATION

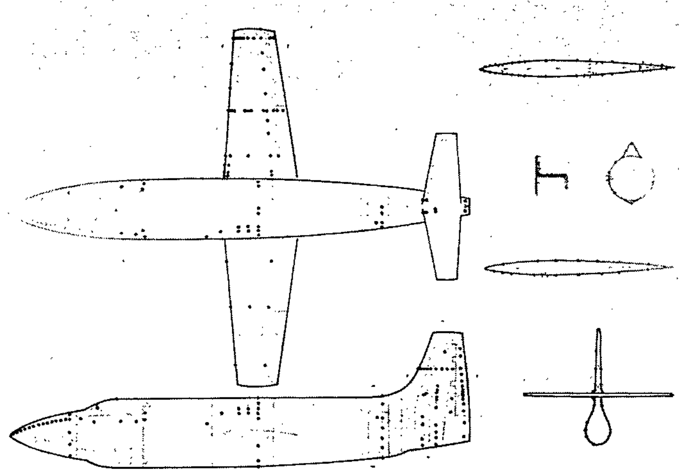


Figure 11. L-263

STRUCTURES RESEARCH

TYPES

- LOADS
- HIGH TEMPERATURES
- RAPID HEATING
- AERO-THERMO-ELASTICITY

FACILITIES

- TESTING MACHINES
- OVENS AND FURNACES
- RADIANT HEATERS
- JETS AND WIND TUNNELS
- ROCKET MODELS
- RESEARCH AIRPLANES

Figure 12. L-264

COMPRESSION CREEP APPARATUS

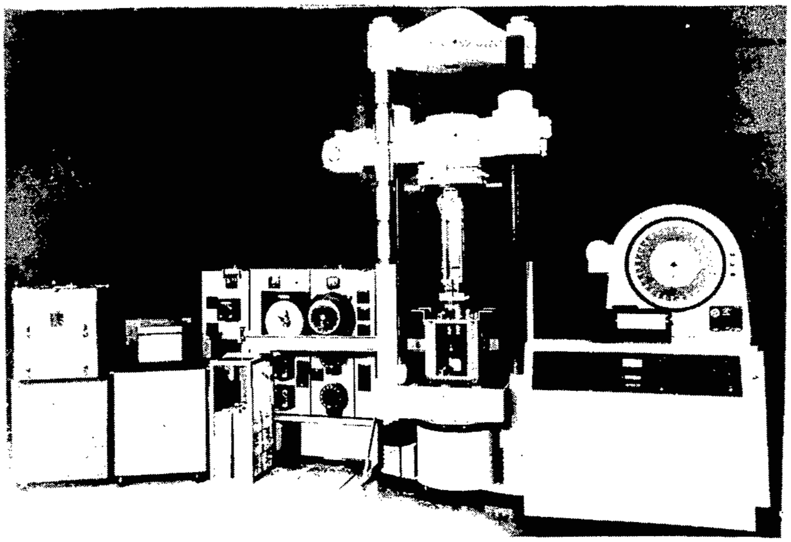


Figure 13. L-265

CREEP TEST EQUIPMENT

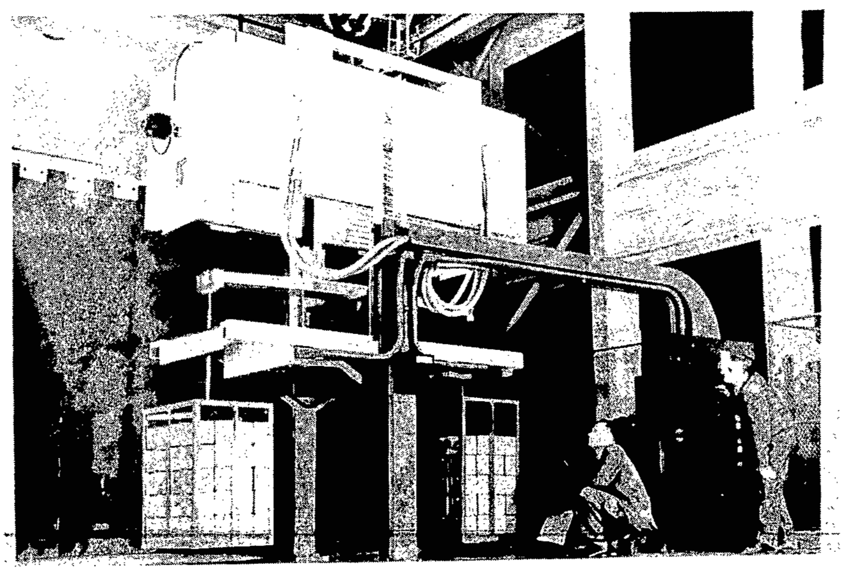


Figure 14. L-266

CARBON-ROD HEAT RADIATOR

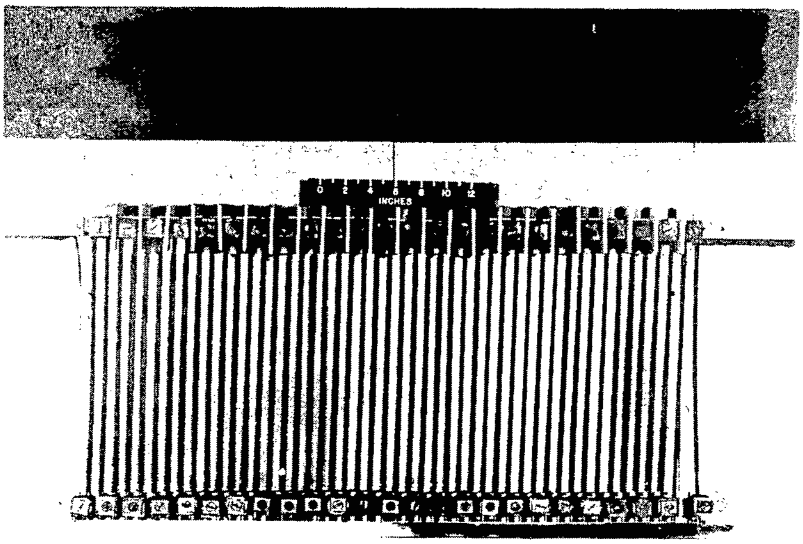


Figure 15. L-267

QUARTZ-LAMP HEAT RADIATORS

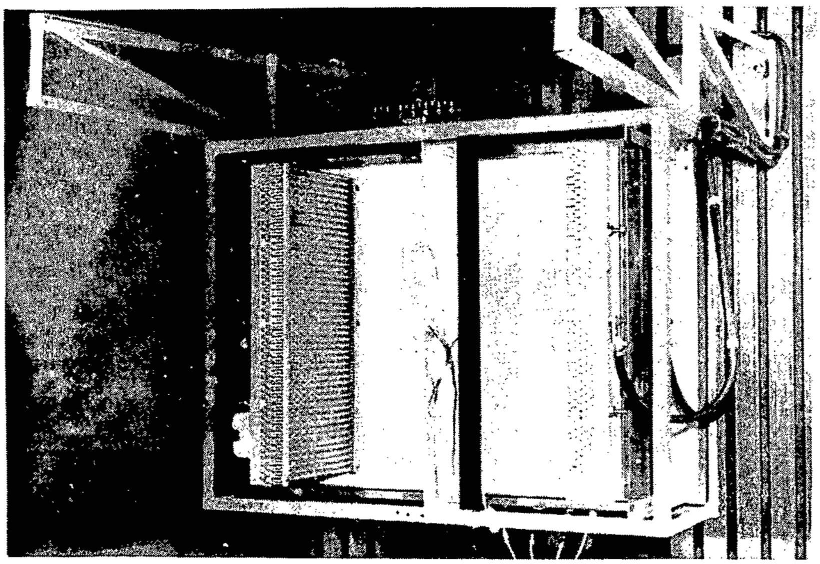


Figure 16. L-268

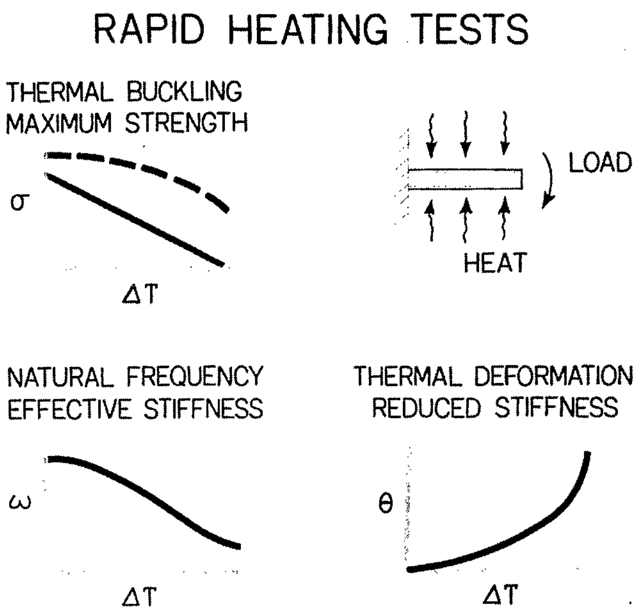


Figure 17. L-269

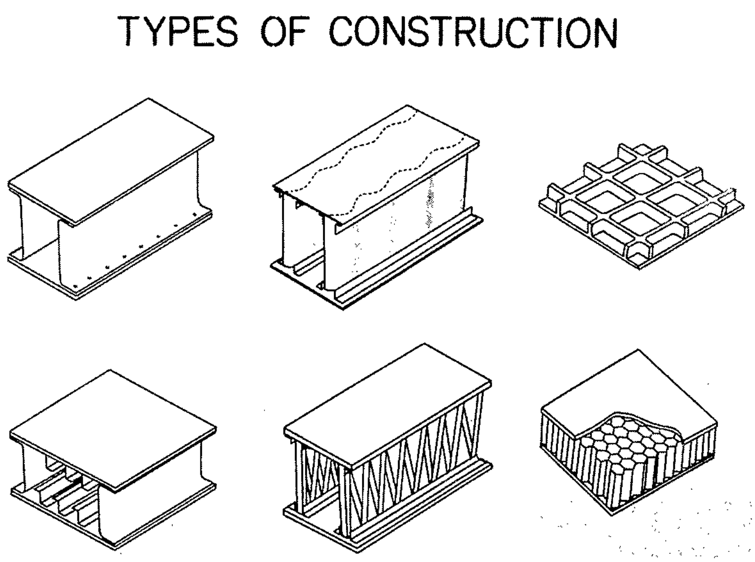


Figure 18. L-270

HEATING AND LOADING OF BOX BEAM

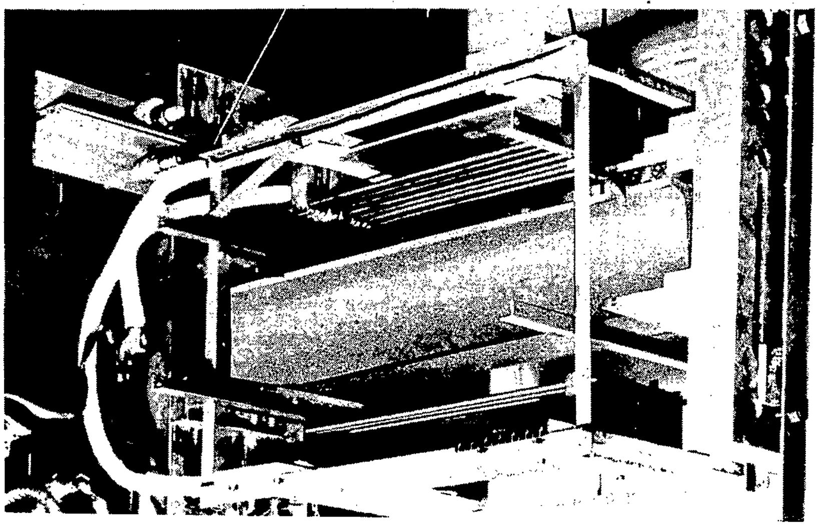


Figure 19. L-271

HEATING & LOADING MISSILE WING

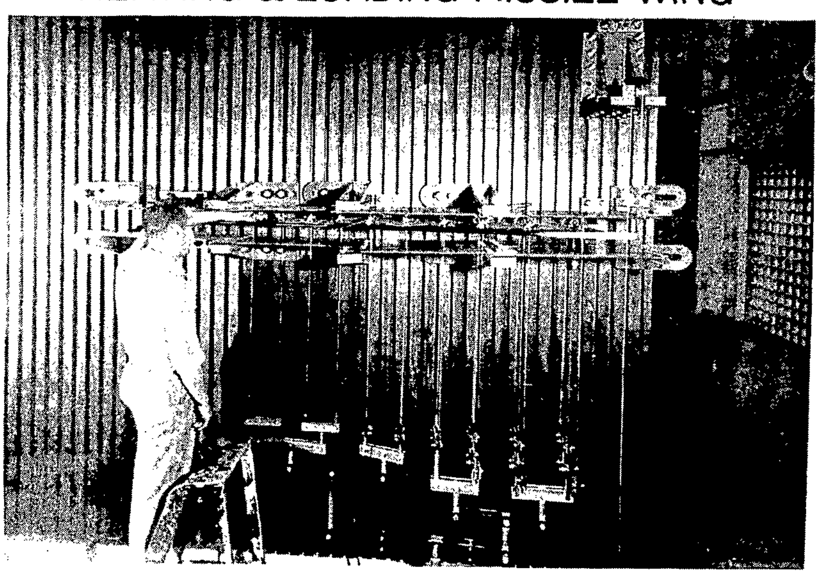


Figure 20. L-272

JET TEST OF WING STRUCTURE

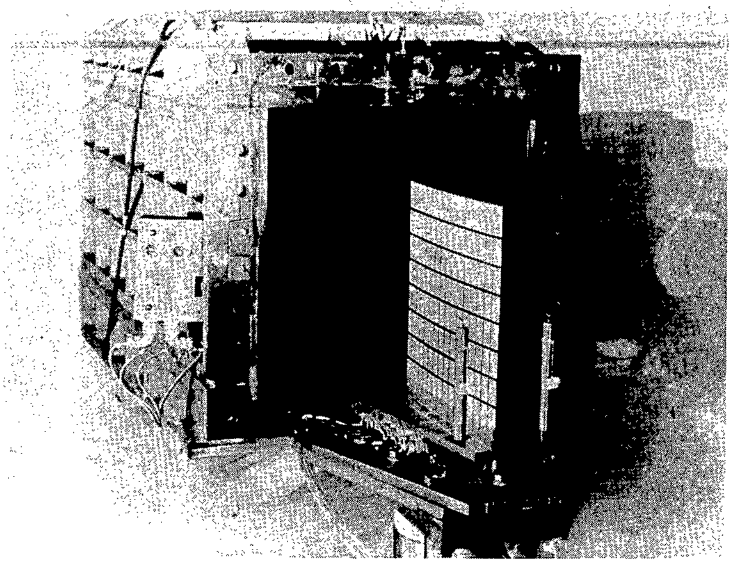


Figure 21. L-273

BASIC REQUIREMENTS HIGH TEMPERATURE STRUCTURAL RESEARCH LABORATORY

SIMULATE HEATING
- MAGNITUDE
- DISTRIBUTION

SIMULATE LOADING
- MAGNITUDE
- DISTRIBUTION
- APPLICATION

ACCOMODATE STRUCTURAL MODELS
- CONFIGURATION
- CONSTRUCTION
- SCALING

Figure 22. L-274

OPERATING RANGE HIGH TEMPERATURE
STRUCTURAL RESEARCH LABORATORY

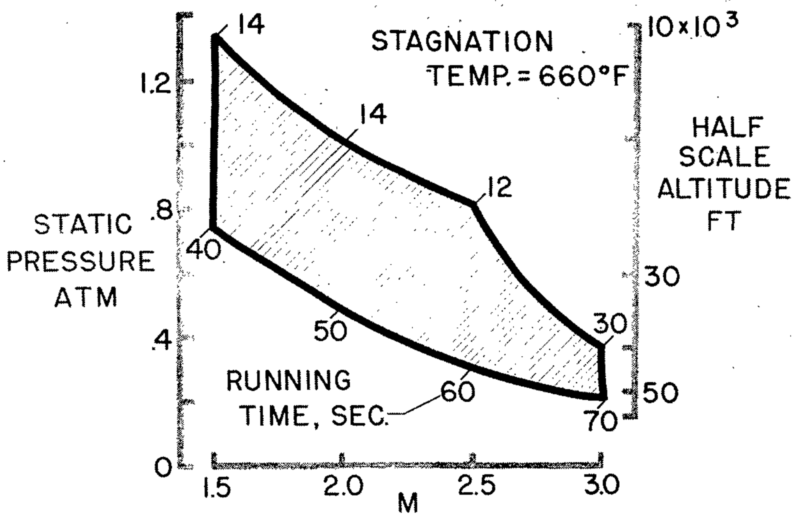


Figure 23. L-275

HIGH TEMP STRUCTURAL RES. LAB.

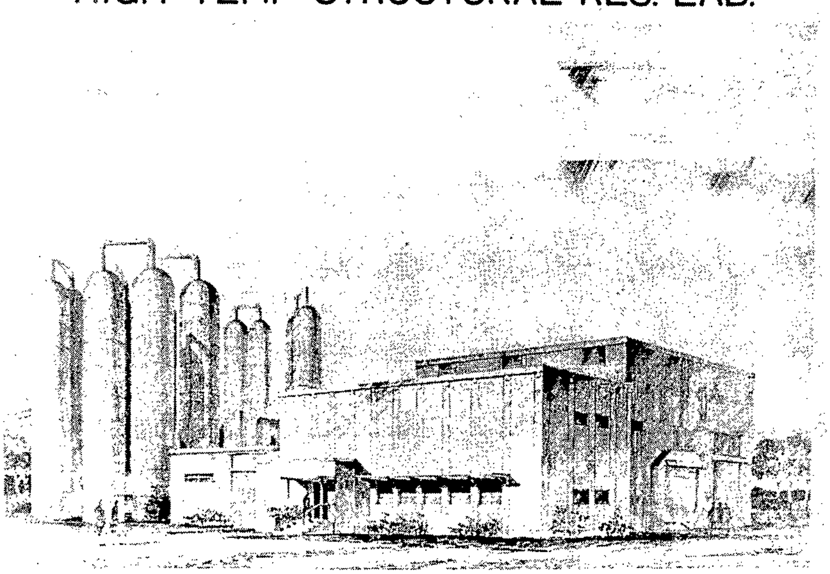


Figure 24. L-276

GENERAL ARRANGEMENT
HIGH TEMPERATURE STRUCTURAL RESEARCH LABORATORY

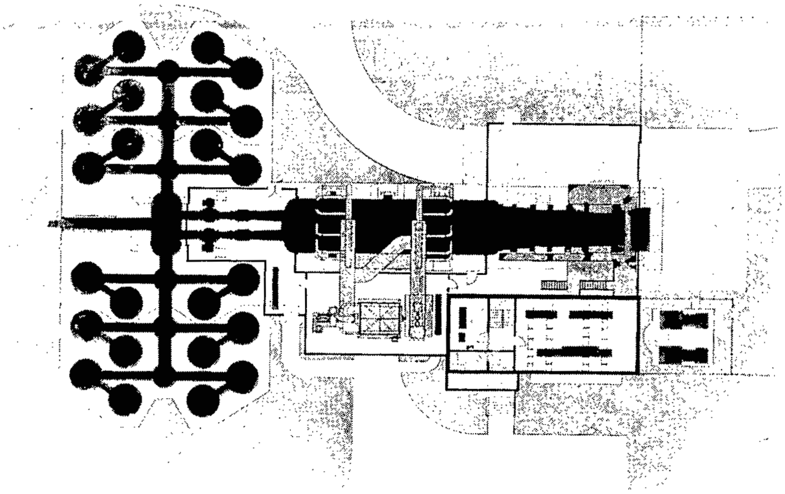


Figure 25. L-277

NOZZLE AND TEST SECTION
HIGH TEMPERATURE STRUCTURAL RESEARCH
LABORATORY

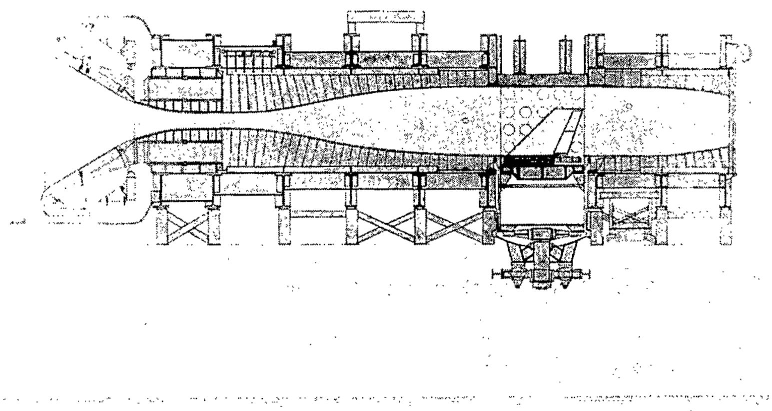


Figure 26. L-278

ATMOSPHERIC ENVIRONMENT

TEMPERATURE
PRESSURE
VELOCITY
CHEMICAL CONTENT
CHEMICAL ACTIVITY

Figure 27. L-280

STRUCTURAL RESEARCH EQUIPMENT

GROUND
- SUPERSONIC TRUE-TEMPERATURE TUNNEL*
- CERAMIC HEAT EXCHANGERS
- SPECIAL COMPRESSORS
- COMBUSTION PRODUCT TUNNEL
- SHOCK TUBES
- FURNACES AND RADIATORS*
- ? ?

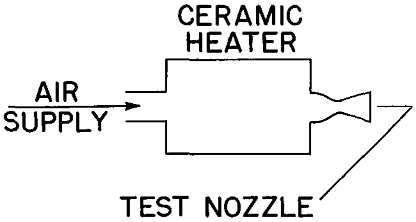
FLIGHT
- GUN-LAUNCHED PROJECTILES
- ROCKET MODELS*
- AIRPLANES

COMBINATION
- FREE-FLIGHT TUNNEL*
- RE-ENTRY TUNNEL

Figure 28. L-281

CERAMIC HEAT EXCHANGERS

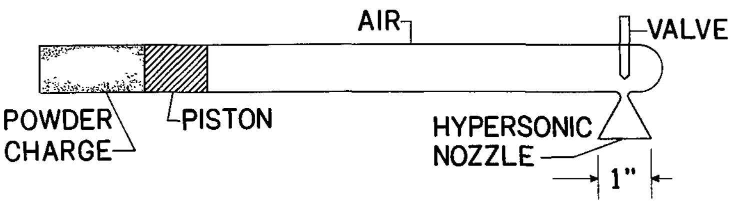
MATERIAL	MELTING POINT, °F
ALUMINA (Al_2O_3)	3450
MAGNESIA (MgO)	4750
ZIRCONIA (ZrO_2)	4900
THORIA (ThO_2)	5970



STAGNATION TEMPERATURE – BELOW MELTING OF CERAMIC
MACH NUMBER – ?
EFFECTIVE ALTITUDE – ?

Figure 29. L-283

HYPERSONIC GUN TUNNEL



STAGNATION TEMPERATURE - UP TO 6,000° F
MACH NUMBER - 7
EFFECTIVE ALTITUDE - 100,000 FT.
DURATION - 1 SEC.

Figure 30. L-282

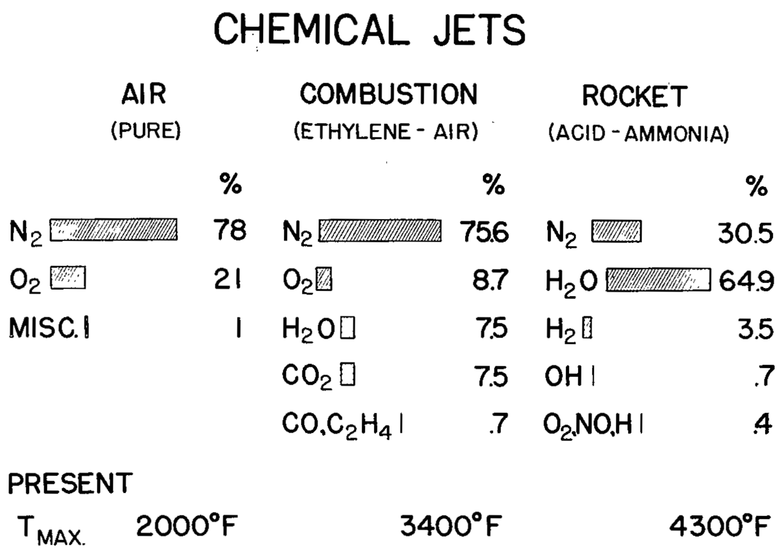


Figure 31. L-284

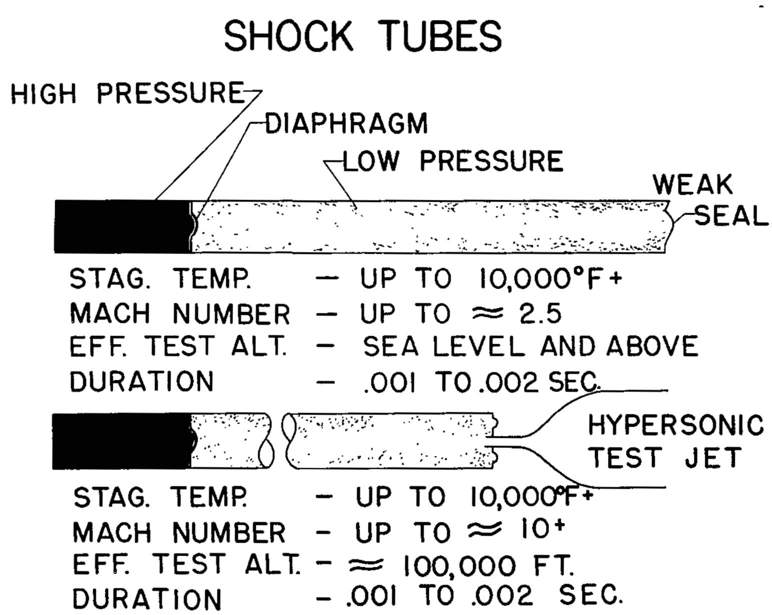
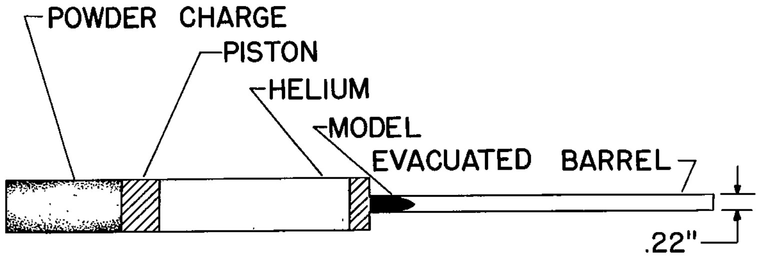


Figure 32. L-285

LIGHT-GAS GUN



STAG. TEMP. - UP TO 25,000°F.

MACH NUMBER - UP TO 15+

EFF. TEST ALT. - SEA LEVEL AND ABOVE

Figure 33. L-286

SUPERSONIC FREE-FLIGHT TUNNEL

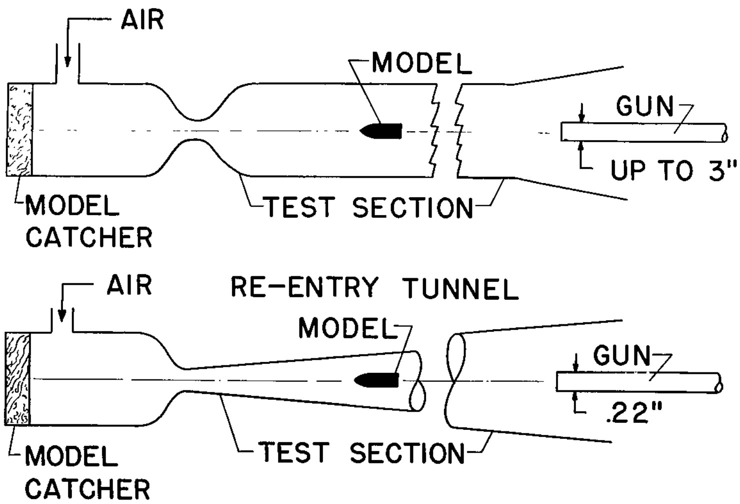


Figure 34. L-287

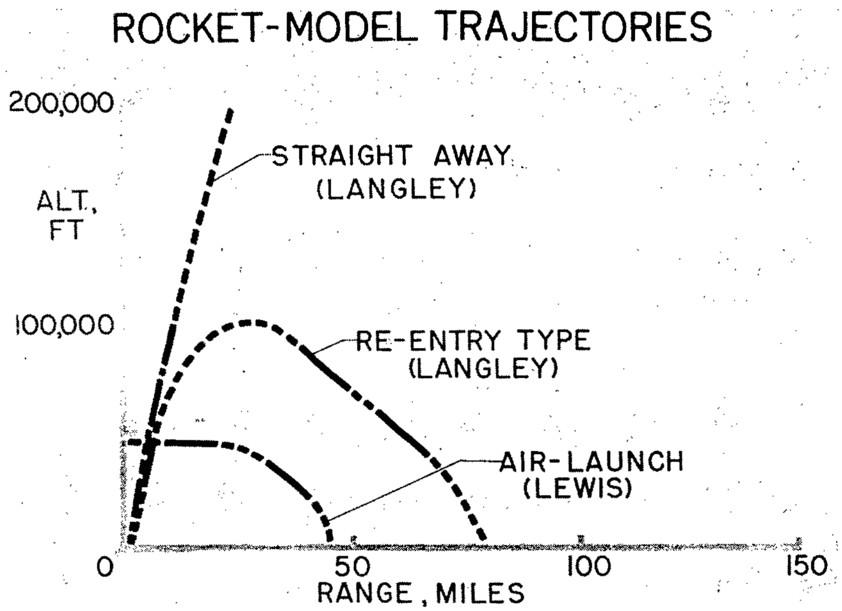


Figure 35. L-288

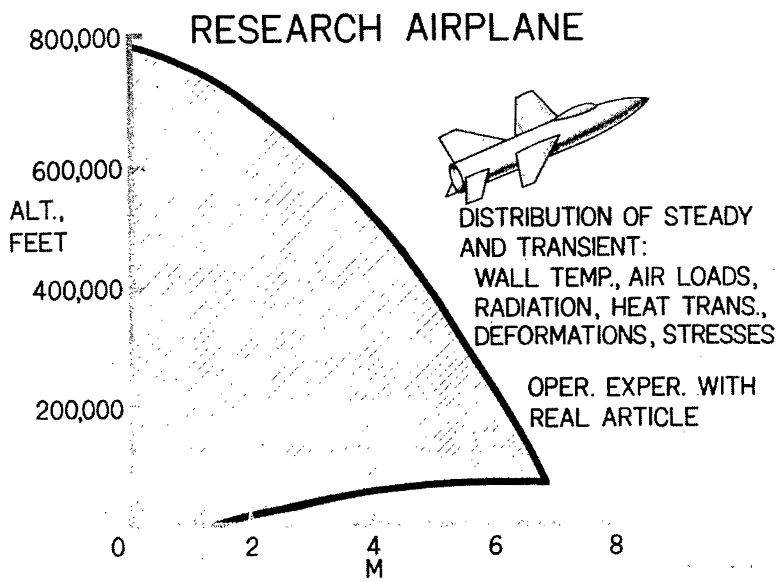


Figure 36. L-289